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(54) **HIGH ENERGY EFFICIENCY BIOMASS
CONVERSION PROCESS**

(75) Inventors: **Andrew D. Livingston**, Independence,
KS (US); **Bijoy J. Thomas**,
Independence, KS (US)

(73) Assignee: **Earth Care Products, Inc.**,
Independence, KS (US)

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(52) **U.S. Cl.** **585/240**; 585/242; 44/605; 44/606;
44/629; 201/25; 202/100; 202/136; 202/235

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See application file for complete search history.

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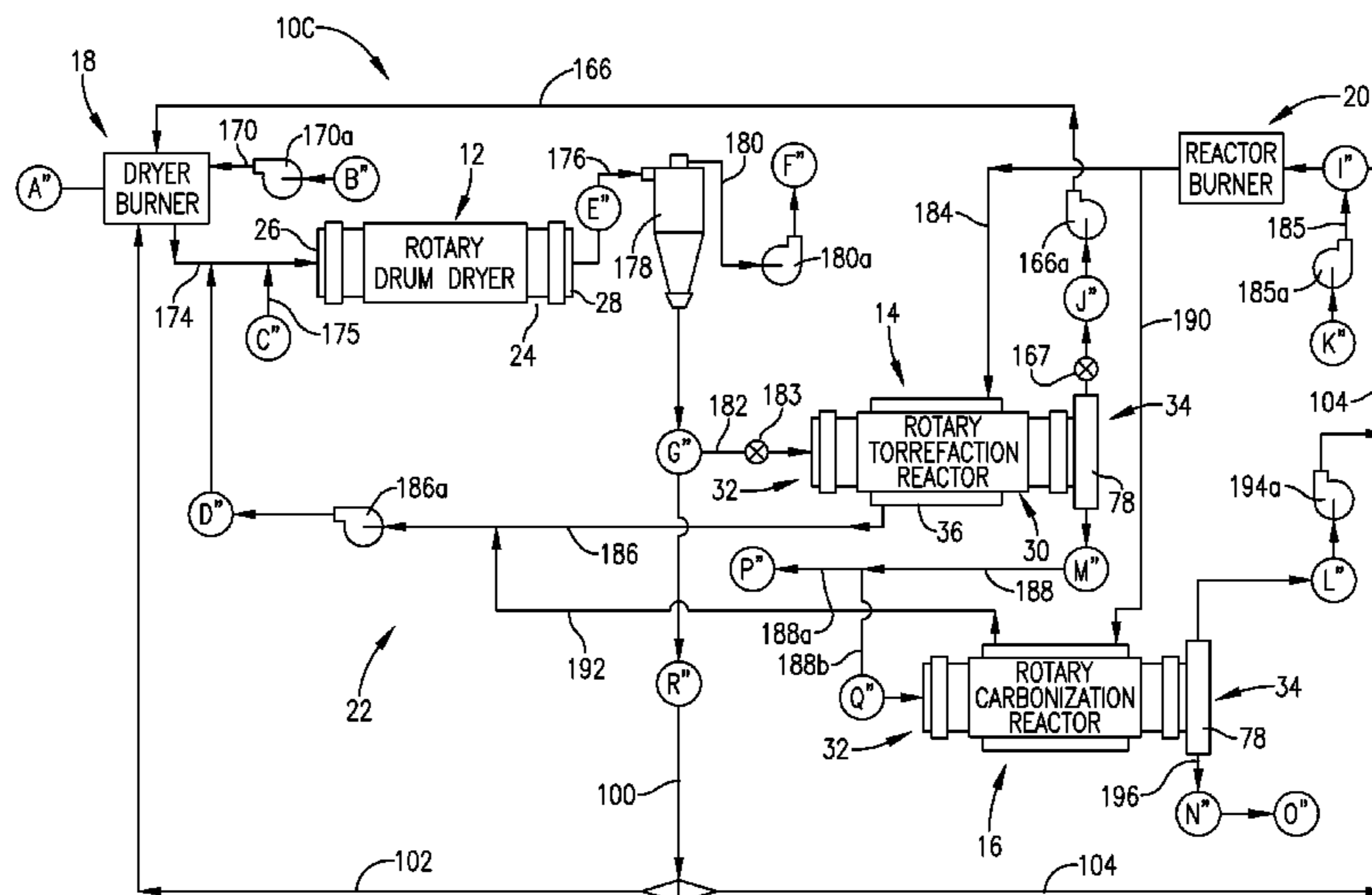
Primary Examiner — Nina Bhat

(74) *Attorney, Agent, or Firm* — Hovey Williams LLP

(57) **ABSTRACT**

Improved, fuel-efficient systems are provided for the processing of biomass, such as wood or crop residues, food waste or animal waste in order to selectively obtain thermally processed final products, such as a combination of torrefied and carbonized final products. The processes involve thermally drying incoming biomass using a dryer employing the hot gas output of a fuel-operated burner. Next, the dried product is torrefied in an indirect torrefaction reactor so as to evolve light volatile organic compounds which are used as a gaseous fuel source for the burner. Some or all of the torrefied product can be recovered, or some or all of the torrefied product is then directed to a separate carbonization reactor coupled with a reactor burner. Carbonization serves to remove most of the remaining VOCs which are used as a gaseous fuel input to the dryer.

19 Claims, 8 Drawing Sheets



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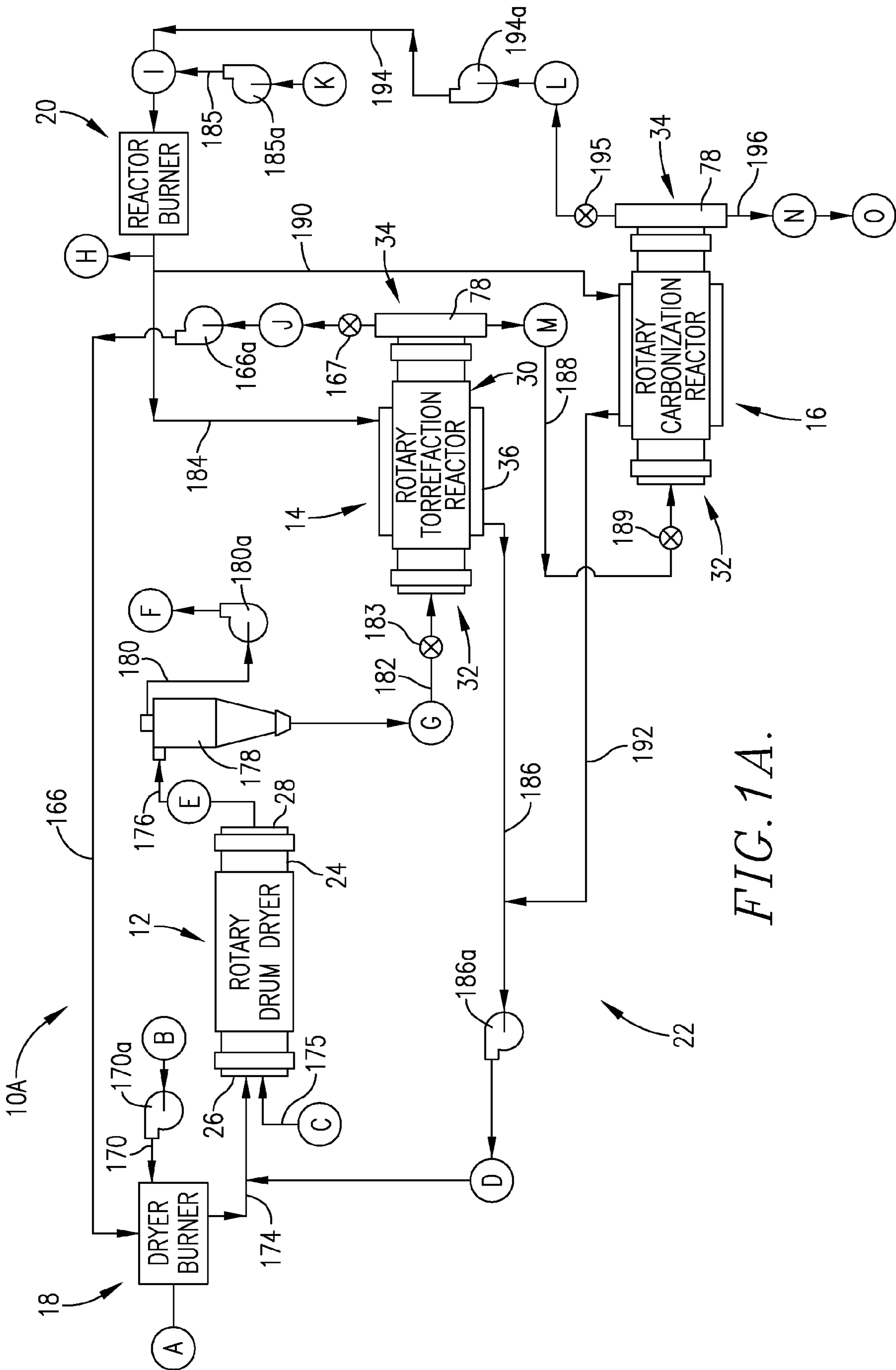


FIG. 1A.

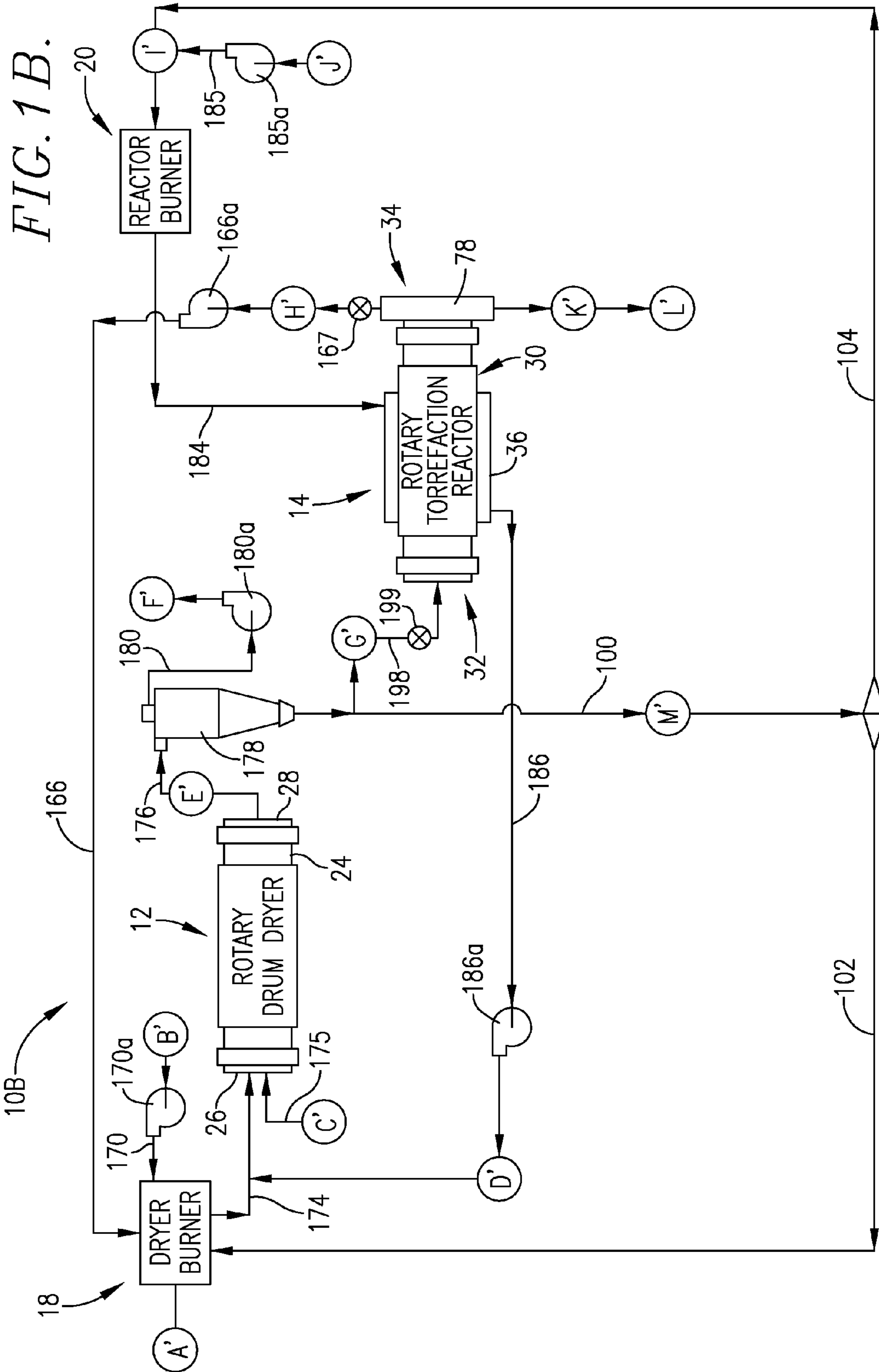
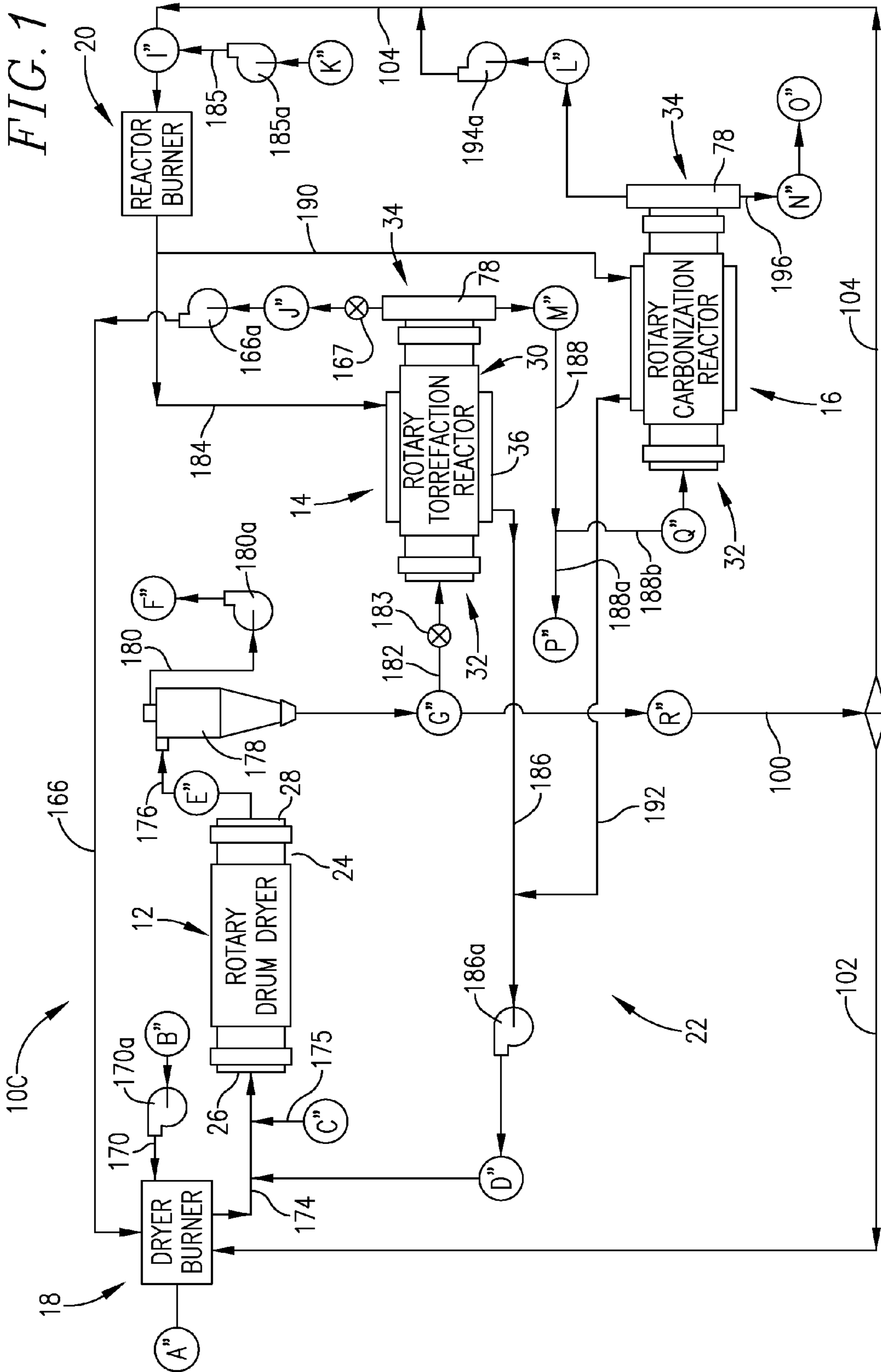


FIG. 1C.



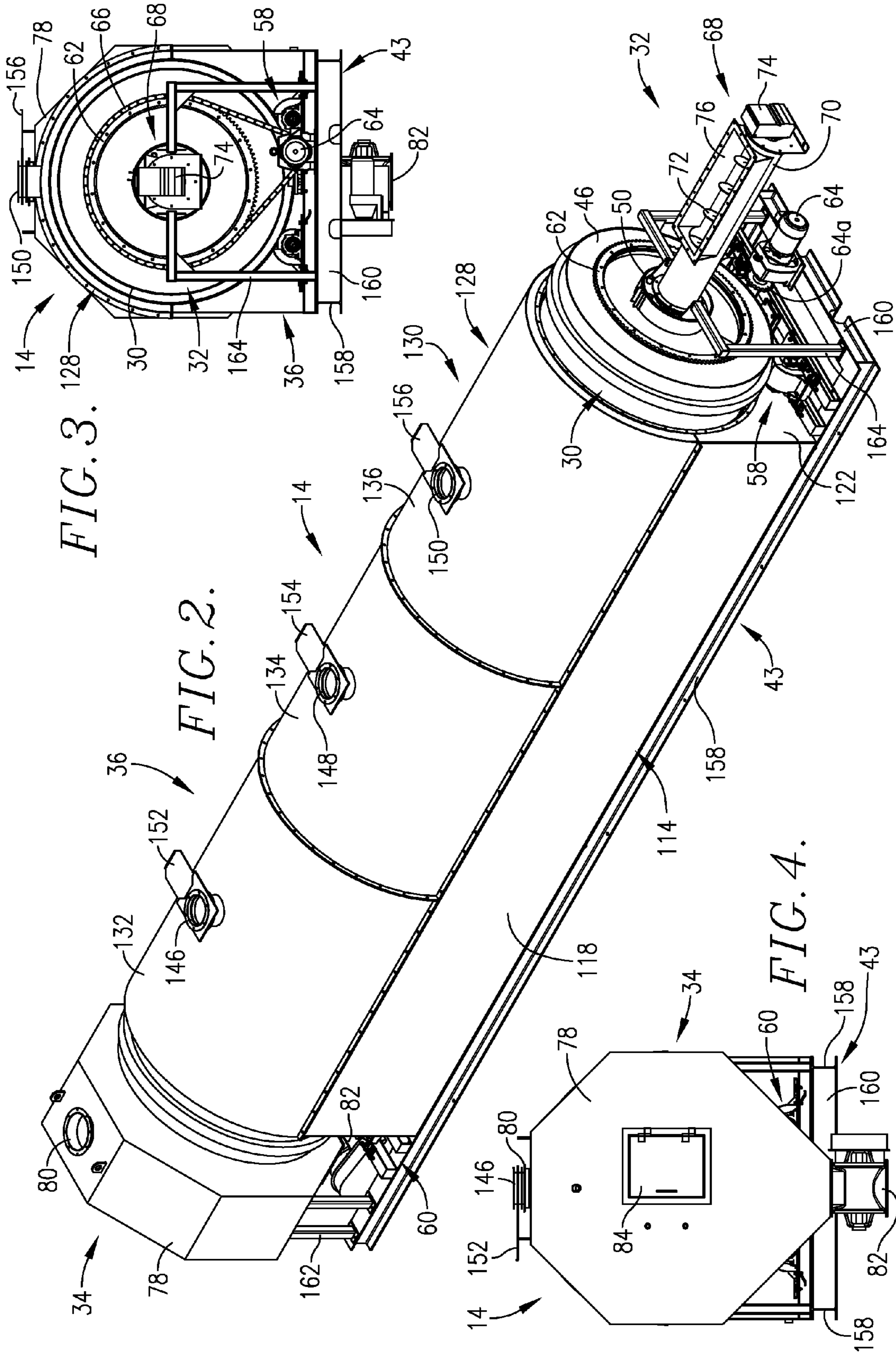
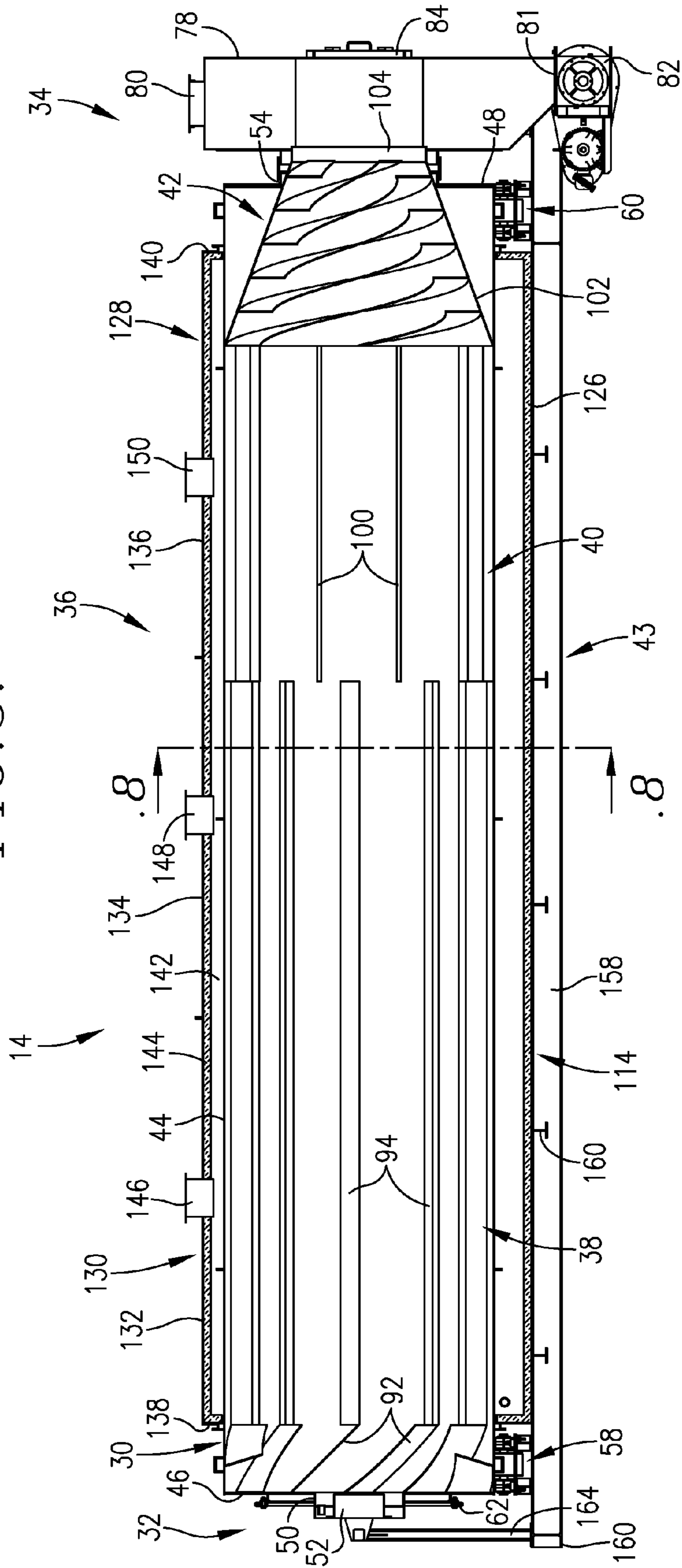


FIG. 5.



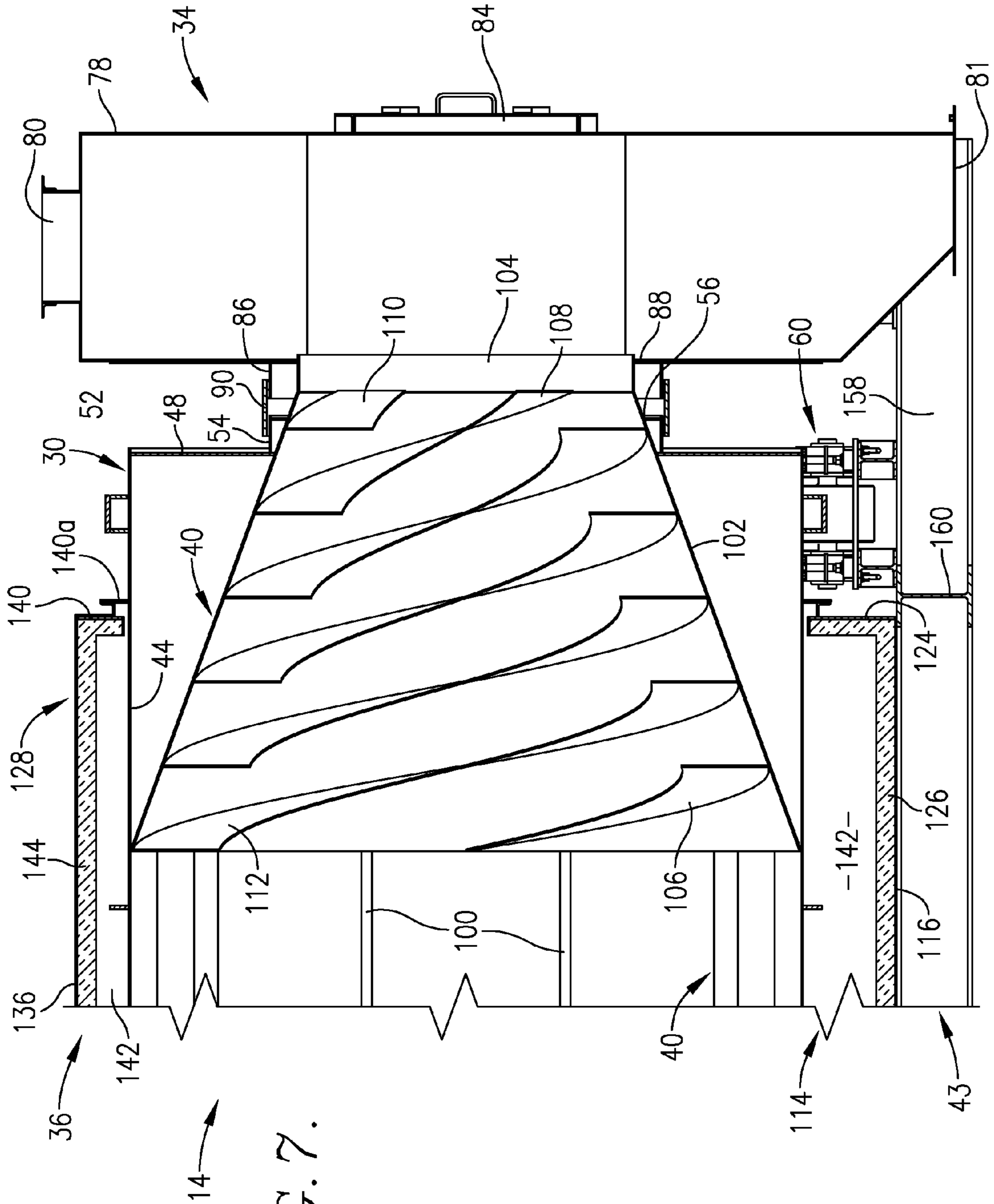


FIG. 7.

HIGH ENERGY EFFICIENCY BIOMASS CONVERSION PROCESS

CROSS-REFERENCE TO RELATED APPLICATION

This application is a continuation-in-part of application Ser. No. 13/347,822, filed Jan. 11, 2012, which is incorporated by reference herein in its entirety.

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention is broadly concerned with methods and apparatus used in the processing of biomass to yield torrefied and/or carbonized (i.e., charcoal) biomass. More particularly, the invention is concerned with such methods and apparatus whereby starting biomass is initially dried and then torrefied in a specialized indirect torrefaction reactor, with the combustible gases evolved from the biomass during torrefaction being used as a source of fuel for the initial biomass drying step. Preferably, at least a portion or all of the torrefied product may be subsequently carbonized in a separate indirect carbonization reactor, with the combustible gases evolved from carbonization also being used as a source of fuel. The processes of the invention are characterized by high energy efficiency, and in some forms the entire thermal energy required for steady-state processing is derived from the evolved combustible gases.

2. Description of the Prior Art

Biomass as understood in the art and as used herein refers to a biological material derived from living, or recently living organisms. In the context of biomass for energy, this is often used to mean plant-based materials, but biomass can equally apply to both animal and vegetable-derived materials. Biomass is carbon-based and is composed of a mixture of organic molecules containing hydrogen, usually including atoms of oxygen, and often with other atoms, including alkali, alkaline earth, and heavy metals. Plant-based biomass is normally lignocellulosic in nature and can be derived from a variety of sources: wood, such as forest waste, arboricultural activities, and wood processing; agricultural residues, such as corn stover and rice straw; grasses, such as switchgrass and miscanthus. Other biomass sources include food waste from food and drink manufacture, preparation, and processing, or industrial waste, municipal solid waste, and animal waste. Biomass as-received generally has a moisture content of 5-80% by weight.

Techniques have been developed in the past for processing biomass to obtain useful fuels. Generally, the native biomass is preliminarily pre-sized, dried and sized, and is thereafter thermally treated to obtain various end products, including torrefied biomass and carbonized (charcoal) biomass. Torrefaction involves thermal processing to evolve combustible organic gases, particularly volatile organic compounds (VOCs). However, the torrefied product still contains heavy VOCs and, if used as a fuel, will have a tendency to "smoke." Carbonization removes most of the remaining VOCs in the torrefied biomass, leaving a residue which is essentially free of smoke-producing compounds and is composed essentially of fixed carbon.

Generally, attempts have been made to carry out many or all stages of the biomass processing in a direct-fired single reactor. This has proved to be problematical because of low production rates and the fact that a single reactor cannot provide the optimum conditions for drying, torrefaction, and

carbonization. Moreover, the throughput of single-reactor systems is relatively low, given that most single carbonization systems are batch systems.

SUMMARY OF THE INVENTION

The present invention overcomes the problems outlined above and provides improved processes and equipment for the torrefaction and carbonization of a starting biomass, preferably on a continuous basis. In general, the processes of the invention comprise first thermally drying the untreated, pre-sized biomass to a reduced moisture content in a dryer using the hot gas output of a fuel-operated burner assembly. Normally, the untreated biomass is reduced to a relatively uniform size (e.g., a maximum cross-sectional dimension of from about 0.125-0.75 in.) using a hammermill or other size-reduction equipment, prior to drying. Advantageously, the drying step is carried out in a rotary dryer using an incoming hot drying gas at a temperature of from about 400-1000° F., more preferably from about 600-800° F. Where the preferred dryer is employed, the drying drum would be rotated at a speed of from about 5-10 rpm. The residence time in the dryer can range from 5 seconds to 8 minutes, depending upon the particle size of the incoming biomass. In the drying step, the moisture content is reduced to a level of from about 2-15% by weight, and more preferably from about 2-4% by weight.

In the next step, at least a portion of the dried biomass is thermally torrefied in an indirect torrefaction reactor different than the dryer using the hot gas output of the fuel-operated burner assembly to generate: (1) a first solid product output stream comprising torrefied biomass; (2) a first burnable gaseous output stream comprising burnable organic constituents evolved from the torrefaction of the biomass; and (3) a first residual gas stream from the torrefaction reactor comprising the gas used to indirectly torrefy the dried biomass. Importantly, at least a portion of the first burnable gaseous output stream is used as at least a part of the fuel to operate the burner assembly. Preferably, the first residual gas stream is also used as a source of heat for the biomass dryer.

In the torrefaction process, the temperature within the reactor should be from about 350-650° F., and more preferably from about 400-600° F., at substantially atmospheric pressure within the reactor. The indirect heating gases to the reactor preferably have a temperature of from about 400-800° F., more preferably from about 500-750° F. The residence time within the torrefaction reactor generally ranges from about 5-25 minutes, and more preferably from about 8-20 minutes. The oxygen content with the torrefaction reactor should be less than about 8% by weight, and more preferably less than about 6% by weight. Where the preferred torrefaction reactor is employed, the shell thereof should be rotated at a rate of from about 0.5-5 rpm, more preferably from about 1-3 rpm. As used herein, "torrefied biomass" refers to a treated biomass product having moisture content of up to about 4% by weight, a reduced volatiles content of from about 10-30% of the volatiles content of the dried, pre-torrefied feedstock, and a fixed carbon content of up to about 35% by weight.

After torrefaction, at least a portion of the solid product output stream is directed to an indirectly heated carbonizing reactor different than the torrefaction reactor, in order to carbonize the torrefied biomass with the hot gas output of the burner assembly to generate: (1) a second solid product output stream comprising carbonized biomass; (2) a second burnable gaseous output stream comprising burnable organic constituents evolved from the carbonization of the torrefied biomass; and (3) a second residual gas stream from the carbonization reactor comprising the gas used to indirectly car-

bonize the torrefied biomass. As in the case of the torrefaction reactor, at least a portion of the second burnable gaseous output stream is used to operate the burner assembly. Similarly, it is preferred to use the second residual gas stream as a source of heat for the dryer.

During carbonization, the temperature within the reactor will range from about 600-1200° F., more preferably from about 700-1100° F., at substantially atmospheric pressure within the reactor. The gases used to indirectly heat the carbonization reactor will be at a temperature of from about 800-1300° F., and more preferably from about 900-1200° F. The VOC-laden output gases from the carbonization reactor recycled to the reactor burner as fuel should have a temperature of from about 600-1000° F., more preferably from about 700-900° F. The residence time of the material within the carbonization reactor will range from about 5-30 minutes, more preferably from about 8-25 minutes. The oxygen content within the carbonization reactor should be less than about 8% by weight, more preferably less than about 4% by weight. Where the preferred carbonization reactor is employed, the shell thereof should be rotated at a rate of from about 0.5-5 rpm, more preferably from about 1-3 rpm. As used herein, "carbonized biomass" or "charcoal" refers to a treated biomass product having moisture content of up to about 4% by weight, a VOC content of up to about 35% by weight and fixed carbon content of up to about 85% by weight.

In preferred forms, the processes of the invention are carried out on a continuous basis to produce either a combination of torrefied and carbonized end products, or entirely carbonized end products. To this end, it is preferred that the hot torrefied product from the torrefaction reactor is substantially immediately and continuously conveyed to the carbonization reactor without any substantial cooling between the reactors. As used herein, the term "different" or "separate" with respect to the torrefaction and carbonization reactors refers to the fact that the operational parameters (e.g., temperature, residence time, oxygen content) of the two reactors may be independently controlled. In preferred forms, the two reactors are physically separate with conveying apparatus therebetween; however, a continuous structure containing independently controllable zones would also have different or separate reactors. As noted, the torrefaction and carbonization reactors are indirect, i.e., the dried biomass is torrefied without direct thermal contact between the dried biomass and the heating gases and, similarly, the torrefied biomass is carbonized without direct contact between the torrefied biomass and the heating gases.

Preferably, the burner assembly comprises separate dryer and reactor burners respectively operably coupled with the biomass dryer and the torrefaction reactor; and where a carbonization reactor is employed, the reactor burner is also coupled with this reactor. Also, when it is desired to produce only a torrefied biomass or both torrefied and carbonized biomass, a portion of the dried, pre-torrefied solid product output stream from the dryer is directed to the burner assembly as a part of the fuel for the operation thereof.

The preferred torrefaction and carbonization reactors of the invention are substantially identical, save for the materials used in the construction thereof. Thus, these reactors comprise an elongated, axially rotatable shell having a biomass input adjacent one end thereof and a treated biomass output adjacent the other end thereof, with a housing in surrounding relationship to the shell and defining with the shell an indirect heating zone, and including a hot gas inlet operable to receive hot gas for indirectly thermally treating biomass within the shell, and a gas outlet. The outlet includes a frustoconical wall with internal spiral fighting along the length thereof, with the

wall secured to the shell and rotatable therewith. The spiral fighting is preferably in the form of a number of individual spiral walls circumferentially spaced from one another around the frustoconical wall. Further, it is preferred to employ a series of internal flights along the length of the shell and each including a first segment secured to the internal surface of the shell, and a second segment oriented at an angle relative to the first segment.

BRIEF DESCRIPTION OF THE DRAWINGS

FIG. 1A is a schematic flow diagram illustrating the important components and operation of the preferred biomass conversion system of the invention, for the production of a charcoal end product;

FIG. 1B is a schematic flow diagram illustrating the important components and operation of the preferred biomass conversion system of the invention, for the production of torrefied end product;

FIG. 1C is a schematic flow diagram illustrating the important components and operation of the preferred biomass conversion system of the invention, for the production of both torrefied and charcoal end products;

FIG. 2 is a front perspective view of the rotary torrefaction reactor forming a part of the systems of FIGS. 1A-1C;

FIG. 3 is a front elevation of the reactor illustrated in FIG. 2, with parts broken away to reveal the construction thereof;

FIG. 4 is a rear elevational view of the reactor of FIG. 2;

FIG. 5 is a vertical sectional view of the reactor illustrated in FIG. 2;

FIG. 6 is an enlarged, fragmentary sectional view illustrating the details of construction of the front input end of the reactor of FIG. 2;

FIG. 7 is an enlarged, fragmentary sectional view illustrating the details of construction of the rear output end of the reactor of FIG. 2; and

FIG. 8 is a vertical view taken along line 8-8 of FIG. 5.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENT

Turning now to the drawings, and particularly FIGS. 1A-1C, biomass conversion systems 10A, 10B, and 10C are schematically illustrated. The system 10A is designed to convert starting biomass from a variety of sources into a carbonized or charcoal product; system 10B is designed to convert the biomass to a torrefied product; and system 10C is designed to simultaneously produce both charcoal and torrefied products. As explained below, all of the systems 10A-10C further produce gaseous (VOC) fuel streams and hot gas output streams to provide a substantial fraction of thermal energy requirement for the equilibrated, steady state operation of the systems, and, in the cases of systems 10B and 10C, dried solid biomass fuel streams. A prime goal of the invention is to operate the systems 10A-10C so as to thereby supply a substantial fraction (preferably at least about 80% thereof, more preferably at least about 90% thereof, and most preferably substantially all) of the thermal energy needed in the steady state operation of the systems.

System 10a for the Production of Charcoal Products (FIG. 1A)

The principal components of the charcoal system 10A are a conventional rotary drum dryer 12, a rotary torrefaction reactor 14, a rotary carbonization reactor 16, a conventional dryer burner 18, a conventional reactor burner 20, and a conduit assembly 22 which operably interconnects the foregoing components.

The rotary drum dryer **12** is preferably of the type described in U.S. Pat. No. 7,155,841, incorporated by reference herein in its entirety. The dryer **12** includes an elongated, circular in cross-section, axially rotatable dryer shell **24** with an input **26** and an output **28**. Internally, the dryer **12** has axially spaced apart first and second drying sections each equipped with a turbulator and a downstream serpentine flow section (not shown). The turbulators are designed to divert portions of a product/air stream in different directions respectively to achieve intense mixing within the shell **24**.

The torrefaction reactor **14** is illustrated in detail in FIGS. 2-8 and broadly includes an elongated, horizontally extending, generally circular in cross-section rotatable metallic (carbon steel) shell **30** with an input assembly **32**, and opposed output assembly **34**, and a multiple-piece insulative housing **36** surrounding the shell **30**. Internally, the shell **30** is equipped with an input flight assembly **38**, an output flight assembly **40**, and a frustoconical, spiral outlet **42**. A lowermost frame assembly **43** supports the shell **30** and housing **36**, and the related equipment described below.

The shell **30** includes a cylindrical main body **44** with an input end wall **46** and an output end wall **48**. The wall **46** includes a central projection **50** defining a tubular inlet **52**, whereas the wall **48** likewise has a central projection **54** defining an outlet opening **56**. The shell **30** is designed to rotate during operation of the reactor **14** and, to this end, the input and output ends of the reactor are provided with conventional trunnion assemblies **58** and **60**. In addition, the input end of the shell **30** is equipped with a circular drive sprocket **62**, as well as a drive motor **64**; a drive chain **66** is operatively coupled between the output **64a** of motor **64** and the drive sprocket **62** so as to effect rotation of the shell **30** at a desired rotational speed (FIGS. 2 and 3).

The input assembly **32** of the shell **30** includes an elongated, tubular auger assembly **68** having a casing **70**, an internal conveying auger **72** driven by motor **74**, and an inlet opening **76**. As will be appreciated, rotation of auger **72** serves to convey material to be processed into the interior of shell **30**.

The output assembly **34** includes a stationary outer housing **78** having an upper gaseous outlet **80**, a lower solids output **81**, an airlock **82** in communication with output **81**, and a central access door **84**. The airlock **82** includes a rotary airlock permitting flow of solids from output **81**, and moreover serves to prevent the escape of VOC's. The rear wall of the housing **78** further has a circular flange **86** which is in alignment with outlet opening **56**, and a housing input aperture **88**. A circular, circumferentially extending seal connector **90** extends around the projection **54** of output end wall **48** and the flange **86**, and serves to operably interconnect the shell **30** and housing **78**.

The input flight assembly **38** (FIG. 6) includes a plurality of circumferentially spaced apart, spirally oriented flights **92** which extend from the inner surface of input end wall **46**. The assembly **38** further has a series of equally circumferentially spaced apart angular flights **94** which extend from the flights **92** along a majority of the length of the shell **30**. Each flight **94** includes an inwardly projecting segment **96** welded to the inner surface of shell **30**, and an oblique segment **98** extending from the inboard end of the segment **92** (FIG. 8).

The output flight assembly **40** includes a series equally circumferentially spaced apart, radially inwardly extending rectilinear flights **100**, which are located substantially equidistantly between the upstream angular flights **94**. The flights **100** extend from the ends of the angular flights **94** up to the spiral outlet **42** (FIG. 5).

The spiral outlet **42** includes an open-ended frustoconical wall **102** which is secured to the inner surface of shell **30** and to the inner edge of the outlet opening **56** (FIG. 7) in order to rotate with the shell **30**. The output end of the wall **102** includes a short cylindrical section **104** which extends into the output aperture **88**. Internally, the wall **102** is equipped with a series of four equally circumferentially spaced apart spiral flights **106**, **108**, **110**, **112**.

The insulated housing **36** includes a lower section **114** having a bottom wall **116**, upstanding, opposed sidewalls **118**, **120**, and opposed end walls **122**, **124**, and a series of lower hot gas inputs (not shown). As best seen in FIG. 8, the sidewalls **118**, **120** extend upwardly approximately to the rotational axis of shell **30**, and the walls **116-124** are equipped with an inner layer of refractory thermal insulation **126**. The housing **36** also has an upper arcuate section **128**, including an elongated, sectionalized primary wall section **130** with end-to-end interconnected sections **132**, **134**, and **136**, and input and output end walls **138**, **140**, respectively extending from the sections **132** and **136**. The section **128** covers the upper half of the shell **30** and is secured to lower section **114**. As best seen in FIGS. 6 and 7, the end walls **138**, **140** extend into close proximity with the rotatable shell **30**, and corresponding seals **138a**, **140a** provide a sealing engagement with the shell **30**. In this fashion, the sections **114** and **128**, cooperatively define an enclosed, indirect heating zone **142** around shell **30**. The upper section walls **132-136** also have an internal layer of refractory thermal insulation **144**.

Each of the sections **132-136** has an upstanding port **146**, **148**, and **150**, and a shiftable slide gate **152**, **154**, and **156**, allowing selective opening and closing of the associated ports **146-150**. The ports **146-150** serve as output ports for the introduction of hot gas to the dryer **12**.

The frame assembly **43** includes fore and aft extending primary rails **158** on opposite sides of the housing **36**, with cross-rails **160** extending and interconnected to the rails **158** along the lengths thereof. Additionally, upstanding struts **162** are provided adjacent the housing **78** in order to support the latter, along with an inverted, U-shaped support **164** coupled with auger assembly **32**.

The carbonization reactor **16** is essentially identical with the torrefaction reactor **14**, except that the metallic components thereof are formed of a high temperature alloy in lieu of carbon steel. Moreover, insulative housing of the reactor **16** is equipped with castable refractory, which can withstand temperatures up to 2200-2500° F., similar to the refractory material used in the torrefaction reactor **14**. Accordingly, the same reference numerals are used in describing and depicting the carbonization reactor.

The conduit assembly **22** interconnects the above-described components to form a complete, operative system. The assembly **22** includes a gaseous fuel input conduit **166** with a blower **166a** and airlock **167**, a combustion air input conduit **170** with a blower **170a**; both of the conduits **166** and **170** are coupled with dryer burner **18**. An output conduit **174** extends from the output of dryer burner **18** to the input assembly **26** of drum dryer **12**, in order to deliver hot combustion gas to the latter for initial drying of incoming biomass. A biomass input conduit **175** is also coupled with input assembly **26** to provide incoming biomass to the system **10A**.

A solids/gas output conduit **176** is provided between the output **28** of drum dryer **12** and the input of a conventional cyclone separator **178**, which serves to separate the solid and gaseous fractions received from the output **28** of drum dryer **12**. A gaseous output conduit **180** provided with a blower **180a** extends from the upper gaseous output of cyclone **178** to an atmospheric vent. A solids output conduit **182**, equipped

with an airlock **183**, extends from the lower solids output of cyclone **178** to the input assembly **32** of torrefaction reactor **14**. The provision of airlocks **82**, **167**, and **183** prevents entrance of ambient air into the reactor **14**. As such, the preferred oxygen-deprived atmosphere within the reactor **14** may be created and controlled.

A hot gas input conduit **184** from the output of reactor burner **20** extends to one of the ports **146-150** of the shell **36** of reactor **14** in order to supply the indirect heat necessary to torrefy the incoming solids from cyclone separator **178**. A separate conduit **185** with blower **185a** provides combustion air to the burner **20**. A conduit **186** equipped with a blower **186a** is coupled between another of the ports **146-150** of the shell **36** and conduit **174**, for delivery of additional drying hot gas to the dryer **12**. The hot VOC-laden gas recovered in the output assembly of the torrefaction reactor is conveyed by line **166** equipped with blower **166a** to the input of burner **18**.

A torrefied solids output conduit **188**, equipped with an airlock **189**, extends from the airlock **82** of reactor **14** to convey the torrefied product to the input assembly **32** of carbonization reactor **16**. The dried and torrefied product from reactor **14** is then subjected to a further carbonization reaction within the reactor **16**. To this end, a hot gas input conduit **190** extends from burner **20** to the input ports along the lower half of shell **36** of reactor **16**, and a residual hot gas output conduit **192** extends from the ports **146-150** to conduit **186**, thereby providing another source of drying gas for use in drum dryer **12**. The hot VOC-laden gas recovered in output assembly **34** of reactor **16** is conveyed by line **194** equipped with blower **194a** and airlock **195** to the input of burner **20**. The final charcoal output from the system **10A** is conveyed via conduit **196** from output assembly **34** of reactor **16** via airlock **82** for cooling and collection thereof. In this regard, it is important that the carbonized product be cooled to a temperature which will prevent spontaneous combustion of the product when exposed to ambient air; any conventional cooling apparatus may be used for this purpose. The airlocks **82**, **189**, and **195** prevent entrance of ambient air into reactor **16** during operation thereof.

As will be appreciated from the foregoing description, the overall system **10** is designed to serially process incoming biomass to initially dry the biomass in dryer **12**, to thereupon torrefy the dried biomass in reactor **14**, followed by final carbonization in reactor **16**. Importantly, once the system **10A** reaches an equilibrated, steady-state operation, all of the thermal energy requirements required for the operation of the system are provided in the form of gaseous VOC-laden byproducts generated by the reactors **14** and **16**.

EXAMPLE 1

This is a hypothetical, computer-based example using system **10A** for the conversion of a typical wood chip biomass into charcoal product, and production of all of the thermal energy used in the operation of the system, once the process has achieved steady state operation.

Referring to FIG. 1A, locations A-O are indicated throughout the system **10A**. The following legend sets forth the mass-energy balance for the process at these respective locations.

- A—dryer burner operation
 - 500 BTU/lb
 - 435 lb/hr VOCs
 - 0.22 MMBtu/hr
- B—combustion air to dryer burner
 - 2,327 SCFM
 - 32° F.
 - 40% excess air

- C—biomass infeed to dryer
 - 4,300 lb/hr total
 - 2,365 lb/hr solids
 - 1,935 lb/hr water
- D—hot gases to dryer
 - 11,164 ACFM
 - 21,647 lb/hr
 - 2.21 MMBtu/hr
 - 770° F.
- E—dryer output
 - 2,438 lb/hr total
 - 2,365 lb/hr solids
 - 73 lb/hr water
 - 110° F.
- F—vented exhaust gases
 - 8,000 ACFM
 - 230° F.
- G—torrefaction reactor input
 - 2,438 lb/hr total
 - 2,365 lb/hr solids
 - 73 lb/hr water
- H—exhaust to atmosphere
 - 4,194 ACFM
 - 8,132 lb/hr
 - 2.75 MMBtu/hr
 - 1500° F.
- I—reactor burner
 - 7,300 BTU/lb
 - 1,309 BTU/hr VOC
 - 9.56 MMBtu/hr
- J—VOCs to dryer burner
 - 402 lb/hr
 - 33 lb/hr water
- K—combustion air to reactor burner
 - 6,790 SCFM
 - 32° F.
 - 40% excess air
- L—VOCs to reactor burner
 - 1,276 lb/hr
 - 33 lb/hr water
- M—torrefied biomass from torrefaction reactor
 - 2,003 lb/hr total
 - 2% water
 - 450° F.
- N—carbonized output from carbonization reactor
 - 694 lb/hr total
 - 1% water
 - 600° F.
- O—cooled carbonized output
 - 694 lb/hr total
 - 1% water
 - 270° F.

The hot gas input in line **174** was 623° F., and the dryer **12** operated at a power of 2.42 MMBtu/hr in order to evaporate 1862 lb/hr of water from the biomass infeed. The hot gas input in conduit **184** was 713° F., and the torrefaction reactor **14** operated a power of 3.09 Btu/hr to evolve VOC's from the dried biomass to generate the torrefied output product. The hot gas in line **190** was 854° F., and the reactor **16** operated at a power of 1.51 MMBtu/hr.

Considering an 8000 hr/yr operation of system **10A** the annual output of the carbonized charcoal final product would be 2776 tons with 6.20 tons of starting biomass yielding 1 ton of the final product.

System 10B for the Production of Torrefied Products (FIG. 1B)

Referring to FIG. 1B, the system 10B employs many of the components of system 10a, and accordingly where appropriate the same reference numerals and foregoing descriptions will be used. Given that the system 10B produces only torrefied products, it does not employ the secondary carbonization reactor 16 and related components. Moreover, the solids from cyclone 178 are split, with a fraction delivered to reactor 14, and another fraction delivered to burner 18 and burner 20 as a source of fuel.

In detail, the solids output from conduit 182 from cyclone 178 is split using a conduit 198 equipped with an airlock 199 to deliver a fraction thereof to the input assembly 32 of reactor 14 to yield torrefied product, and the remainder thereof is conveyed by conduit 100; this solids fraction is again split using conduits 102 and 104, for delivery of solid product to the burners 18 and 20 respectively, to provide fuel therefor. The torrefied product from reactor 14 is delivered by line 106 for cooling and recovery thereof. Again, the airlocks 82, 167, and 199 prevent entrance of ambient air into reactor 14.

The system 10B thus sequentially dries and torrefies incoming biomass, and produces both gaseous VOC and solid dried biomass fuel streams which provide a substantial amount of the thermal energy used in the process at steady-state operating conditions.

EXAMPLE 2

This is a hypothetical, computer-based example using system 10B for the conversion of a typical wood chip biomass into torrefied product, and production of thermal energy used in the operation of the system, once the process has achieved steady state operation.

Referring to FIG. 1B, locations A'-M' are indicated throughout the system 10. The following legend sets forth the mass-energy balance for the process at these respective locations.

A'—dryer burner operation
8,000 BTU/lb dried biomass
362 lb/hr dried biomass
2.90 MMBtu/hr

B'—combustion air to dryer burner
1,223 SCFM
32° F.
175% excess air

C'—biomass infeed to dryer
4,300 lb/hr total
2,365 lb/hr solids
1,935 lb/hr water

D'—hot gases to dryer
2,122 ACFM
5,885 lb/hr
0.50 MMBtu/hr
400° F.

E'—dryer output
2,438 lb/hr total
2,365 lb/hr solids
73 lb/hr water
110° F.

F'—vented exhaust gases
8,000 ACFM
230° F.

G'—torrefaction reactor input
1,909 lb/hr total
1,852 lb/hr solids
57 lb/hr water

H'—Mass loss of VOC's

315 lb/hr
26 lb/hr water

I'—reactor burner operation

7,300 BTU/lb
1,309 BTU/hr VOC
9.56 MMBtu/hr

J'—Combustion air to reactor burner

565 SCFM
32° F.
175% excess air

K'—Torrefied product

1568 lb/hr total
2% water
450° F.

L'—Cooled torrefied product

1568 lb/hr total
2% water
270° F.

M'—Dried biomass fuel to dryer and reactor burners

529 lb/hr
3% water
ambient temperature

The hot gas input in line 174 was 622° F., and the dryer 12 operated at a power of 2.90 MMBtu/hr in order to evaporate 1862 lb/hr of water from the biomass infeed. The hot gas input in conduit 184 was 725° F., and the torrefaction reactor 14 operated at a power of 3.09 Btu/hr to evolve VOC's from the dried biomass to generate the torrefied output product.

Considering a 8000 hr/yr operation of system 10B, the annual output of the carbonized charcoal final product would be 6273 tons.

System 10C for the Production of Both Torrefied and Charcoal Products (FIG. 1C)

The system 10C is designed to simultaneously produce torrefied and carbonized final products. The system has many of the components of the previously described system 10A, and certain components from the system 10B. Accordingly, like reference numerals in FIGS. 1A and 1B will be used throughout the ensuing discussion. There are two principal differences between systems 10A and 10C. The first is provision of apparatus for recovering a portion of the torrefied product, with the remaining portion being directed to carbonization reactor 16 via conduit legs 188a and 188b. The second difference is the use of a portion of the solid product derived from the output of cyclone 178 as a source of solid fuel to the dryer and reactor burners 18, 20, via conduits 100, 102, and 104.

EXAMPLE 3

This is a hypothetical, computer-based example using system 10C for the simultaneous conversion of a typical wood chip biomass into torrefied and charcoal products, and production of a substantial part of the thermal energy used in the operation of the system, once the process has achieved steady state operation.

Referring to FIG. 1C, locations A"-Q" are indicated throughout the system 10C. The following legend sets forth the mass-energy balance for the process at these respective locations.

A"—dryer burner—wood/VOC burner
8,000 BTU/lb wood
232 lb/hr wood
1.86 MMBTU/hr

11

B"—combustion air
713 SCFM
32° F.
150% excess air

C"—biomass infeed to dryer
4,300 lb/hr total
2,365 lb/hr solids
1,935 lb/hr water

D"—hot gases to dryer
4,371 ACFM
8,476 lb/hr
1.36 MMBTU/hr
770° F.

E"—dryer output
2,438 lb/hr total
2,365 lb/hr solids
73 lb/hr water
3% moisture
110° F.

F"—vented exhaust gases
8,000 ACFM
230° F.

G"—torrefaction reactor input
2,201 lb/hr total
3% water
110° F.

I"—reactor burner—wood/VOC burner
7,300 BTU/lb VOC
591 lb/hr VOC
8,000 BTU/lb wood
5 lb/hr wood
4.33 MMBTU/hr

J"—VOCs to dryer burner
363 lb/hr
30 lb/hr water

K"—combustion air to reactor burner
3,065 SCFM
32° F.
80% excess air

L"—VOCs to reactor burner
576 lb/hr
15 lb/hr water
O"—wood fuel to burners
237 lb/hr total
0% water
ambient temperature

P"—torrefied product output
1,808 lb/hr total
2% water
450° F.

Q"—recovered torrefied product
904 lb/hr total
2% water
270° F.

M"—carbonized biomass output
313 lb/hr total
1% water
600° F.

N"—cooled carbonized output
313 lb/hr total
1% water
270° F.

The hot gas input to dryer **12** in line **174** was 621° F., and the dryer **12** operated at a power of 3.22 MMBtu/hr in order to evaporate 1862 lb/hr of water from the biomass infeed. The hot gas input in conduit **184** was 758° F., and the torrefaction reactor **14** operated a power of 2.85 Btu/hr to evolve VOC's

12

from the dried biomass to generate the torrefied output product. The hot gas in line **190** was 838° F., and the reactor **16** operated at a power of 1.40 MMBtu/hr.

Considering an 8000 hr/yr operation of system **10C** the annual output of the torrefied product would be 3617 tons, and the output of the carbonized product would be 1253 tons.

We claim:

1. A process for treating biomass containing burnable organic constituents, comprising the steps of:

thermally drying said biomass to a reduced moisture content in a dryer using the hot gas output of a fuel-operated burner assembly;

thermally torrefying at least a portion of said dried biomass in an indirect torrefaction reactor different than said dryer using the hot gas output of said fuel-operated burner assembly to generate: (1) a first solid product output stream comprising hot torrefied biomass; (2) a first burnable gaseous output stream comprising a first portion of the burnable organic constituents evolved from said torrefaction of said biomass; and (3) a first residual gas stream from said torrefaction reactor comprising the gas used to indirectly torrefy said dried biomass; and

carbonizing at least a portion of said hot torrefied biomass from said first solid product output stream in an indirect carbonization reactor different than said torrefaction reactor using a portion of the hot gas output of said burner assembly to generate: (1) a second solid product output stream comprising carbonized biomass; (2) a second burnable gaseous output stream comprising a second portion of the burnable organic constituents evolved from said carbonization of said torrefied biomass; and (3) a second residual gas stream from said carbonization reactor comprising the gas used to indirectly carbonize said torrefied biomass,

said drying, torrefying, and carbonizing steps being carried out continuously.

2. The process of claim **1**, including the step of using at least a part of said first and second burnable gaseous output streams as at least a part of the fuel to operate said burner assembly.

3. The process of claim **1**, including the step of using said at least a part of said first and second residual gas streams as a source of heat for said dryer.

4. The process of claim **1**, said burner assembly including a dryer burner operably coupled with said dryer, and a reactor burner operably coupled with said torrefaction and carbonization reactors, including the steps of using at least a portion of said first burnable gaseous output stream as at least a part of the fuel to operate said dryer burner, and using at least a portion of said second burnable gaseous output stream as at least a part of the fuel to operate said reactor burner.

5. The process of claim **1**, including the step of recovering torrefied biomass from said torrefaction reactor, and recovering carbonized biomass from said carbonization reactor.

6. The process of claim **1**, including the step of carbonizing substantially all of said hot torrefied biomass of said first output stream.

7. The process of claim **1**, including the step of using portions of said dried biomass as fuel for said burner assembly.

8. The process of claim **1**, said first and second burnable gaseous output streams providing the entire fuel requirements needed to operate said burner assembly.

9. The process of claim **1**, including the step of operating said burner assembly to create a hot gas output having a temperature of from about 400 to 1000° F.

13

10. The process of claim 1, said burner assembly including a dryer burner operably coupled with said dryer, and a reactor burner operably coupled with said carbonization reactor.

11. The process of claim 1, including the steps of torrefying said dried biomass in said torrefaction reactor for a period of from about 5 to 25 minutes, and carbonizing the hot torrefied biomass in said carbonization reactor for a period of from about 5 to 30 minutes.

12. The process of claim 1, said torrefaction reactor operable to indirectly torrefy said dried biomass, and said carbonization reactor operable to indirectly carbonize the hot torrefied biomass from said torrefaction reactor.

13. The process of claim 1, said torrefaction and carbonization reactors each comprising an elongated, axially rotatable shell having an input and an output, a housing in surrounding relationship to said shell and defining with the shell an indirect heating zone, said housing including an input for said gaseous output of said burner assembly, and an output for said first and second residual gas streams, respectively.

14. A system for treating biomass containing burnable organic constituents, comprising:

a fuel-operated burner assembly operable to generate hot output gas;

a dryer coupled with said burner assembly and operable to dry said biomass to a reduced moisture content using hot gas from said burner assembly;

an indirect torrefaction reactor coupled with said burner assembly and dryer for receiving dried biomass from the dryer, said torrefaction reactor operable to torrefy said dried biomass using hot gas from said burner assembly to generate: (1) a first solid product output stream comprising hot torrefied biomass; (2) a first burnable gaseous output stream comprising a first portion of the burnable organic constituents evolved from said torrefaction of said biomass; and (3) a first residual gas stream from said

14

torrefaction reactor comprising the gas used to indirectly torrefy said dried biomass; and

an indirect carbonization reactor coupled with said burner assembly and said torrefaction reactor, said carbonization reactor operable to carbonize at least a part of said hot torrefied biomass of said first solid output stream using hot gas from said burner assembly to generate: (1) a second solid product output stream comprising carbonized biomass; (2) a second burnable gaseous output stream comprising a second portion of the burnable organic constituents evolved from said carbonization of said torrefied biomass; and (3) a second residual gas stream from said carbonization reactor comprising the gas used to indirectly carbonize said torrefied biomass.

15. The system of claim 14, said burner assembly including a reactor burner operably coupled with said dryer and a reactor burner operably coupled with said torrefaction and carbonization reactors, respectively.

16. The system of claim 14, including apparatus for conveying at least a part of said first and second burnable gaseous output streams to said burner assembly to serve as fuel for the burner assembly.

17. The system of claim 14, including apparatus for conveying at least a part of said first and second residual gas streams to said dryer as a source of heat for the dryer.

18. The system of claim 14, including a first recovery assembly for recovering torrefied biomass from said torrefaction reactor, and a second recovery assembly for recovering carbonized biomass from said carbonization reactor.

19. The system of claim 14, said torrefaction and carbonization reactors each comprising an elongated, axially rotatable shell having an input and an output, a housing in surrounding relationship to said shell and defining with the shell an indirect heating zone, said housing including an input for said gaseous output of said burner assembly, and an output for said first and second residual gas streams, respectively.

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